ments. Siemens would like to convert all it's single-crystal ingot growth stations to tri-crystal ingots because tri-crystal wafers are much stronger and can be cut much thinner, resulting in up to a 40% reduction in module cost. (Tri-crystal wafers cannot be textured in the current manner and would be less efficient, so Siemens is highly interested in Sandia's plasma-texturing work, through which Si wafers can be textured regardless of their crystalline orientation.)

*(Contact **Doug Ruby**, 505-844-0317, dsruby@sandia.gov)*

Sandia's Mexico program assists with 117-kW hybrid system in Baja California, Mexico

Arizona Public Service, working with the Mexican Federal Electricity Commission, is procuring and installing a 117-kW wind/photovoltaic/diesel hybrid system for a remote community in Baja California, Mexico. Sandia is involved in the design review and is contributing $150,000 of U.S. Department of Energy (DOE) funds and $100,000 of U.S. Agency for International Development (USAID) funds toward the purchase of hardware.

Installation is scheduled to be completed by the end of this calendar year. The hybrid system is to provide electricity to the remote community of San Juanico in the Mexican state of Baja California Sur, and will comprise 100-kW of wind turbines, a 17-kW photovoltaic array, and a 70-kW diesel generator. The system is designed to extend the availability of electricity from 4 hours to 24 hours daily, while reducing overall diesel fuel consumption.

*(Contact **Abbas Akhil**, (505) 844-7308, aaakhil@sandia.gov, or **Charles Hanley**, (505) 844-4435, cjhanle@sandia.gov)*

Sandians make presentations at utility-interconnection workshop in support of Million Solar Roofs

Ward Bower spoke on the National Electrical Code and its impact on the design and installation of photovoltaic systems and John Stevens talked about the IEEE photovoltaic interconnection standard and its implications at the DOE's Chicago Regional Support Office utility-interconnection workshop in East Lansing, Michigan, at the end of June. The workshop was in support of the Million Solar Roofs Initiative, and electric utilities, photovoltaic system designers/installers, and university researchers were represented.

*(Contact **John Stevens**, 505-844-7717, jwsteve@sandia.gov, or **Ward Bower**, 505-844-5206, wibower@sandia.gov)*

Sandia hosts photovoltaic battery-charging workshop at ASES Solar '98

Sandia presented a Photovoltaic Hybrid Battery Workshop at the SOLAR98 conference held in Albuquerque, New Mexico, in June. The workshop was designed to provide information on basic lead-acid battery technology and charging requirements specifically for photovoltaic power systems.

Field experience and laboratory testing are continuing at Sandia and the Florida Solar Energy Center to more accurately define battery requirements, improve photovoltaic hardware, and establish the needs of photovoltaic systems in stand-alone and hybrid power systems. The goal is to provide better information to photovoltaic system integrators to allow them to improve their system designs.

*(Contact **Tom Hund**, 505-844-8627, tdhund@sandia.gov)*

Note on recent publication

The recent SAND98-0499 report Trimode Optimizes Hybrid Power Plants - Final Report: Phase II published in July 1998 was erroneously published as a Sandia Contractor Report. The report should have been published as an account of hardware development for a Department of Energy, Small Business Innovative Research (SBIR) Grant. It should be noted that the Sandia National Laboratories testing reported therein was in support of hardware development as part of the SBIR grant and was funded by Abacus Controls, Inc. The laboratory testing performed by Sandia was developmental testing and was not a field certification.

*(For more information, contact **Ward Bower** (505)844-5206, wibower@sandia.gov).*

Sandians present technical papers at the 2nd World Conference and Exhibition on Photovoltaic and Solar Energy Conversion

Sandians presented the following papers as first authors at the 2nd World Conference and Exhibition on Photovoltaic and Solar Energy Conversion, Vienna, Austria, July 6-10, 1998. All can be found on Sandia's Website at www.sandia.gov/pv. The abstracts are as follows:

- Russell Bonn, Jerry Ginn, Sigifredo Gonzalez and G. A. Kern. *Results of Sandia National Laboratories Grid-Tied Inverter Testing*

The paper proposes a definition for a "non-islanding inverter" and presents methods that can be used to implement such inverters. References to earlier work on the subject are included. Justification for the definition is provided on a theoretical basis and uses results from tests conducted at Sandia and at Ascension Technology.

- David L King, William E. Boyson, Barry R. Hansen, and Ward I. Bower. *Improved Accuracy for Low-Cost Solar Irradiance Sensors*

Accurate measurements of broadband (full spectrum) solar irradiance are fundamental to the successful implementation of solar power systems, both photovoltaic and solar thermal. This paper demonstrates how to achieve acceptable accuracy (+ 3%) in irradiance measurements using sensors costing less than one-tenth that of typical thermopile devices. The low-cost devices use either silicon photodiodes or photovoltaic cells as sensors, and in addition to low cost, have several operational advantages.

- David L. King, Jay A. Kratochvil, William E. Boyson, and Ward I. Bower. *Field Experience with a New Performance Characterization Procedure for Photovoltaic Arrays*

Test methods that successfully separate the interacting, time-of-day dependent influences of solar irradiance, operating temperature, solar spectrum, and solar angle-of-incidence have now been developed. They have resulted in a new array performance model that is reasonably simple, yet accurately predicts performance for all operating conditions. This paper describes the new model, outdoor tests required to implement it, results of field tests for five arrays of different technologies, and the evolution of the model into a numerical tool for designing and sizing photovoltaic arrays based on annual energy production.

- *Douglas S. Ruby, P. Yang, S. Zaidi, S. Brueck, M. Roy and S. Narayanan. Improved Performance of Self-Aligned, Selective-Emitter Silicon Solar Cells.*

We improved a self-aligned emitter etchback technique that requires only a single emitter diffusion and no alignments to form self-aligned, patterned-emitter profiles. We used full-size multicrystalline silicon (ms-Si) cells processed in a commercial production line and performed a statistically designed multiparameter experiment to optimize the use of a hydrogenation treatment to increase performance. We obtained an improvement of almost a full percentage point in cell efficiency when the self-aligned emitter etchback was combined with an optimized three-step PECVD-nitride surface passivation and hydrogenation treatment.

Sandians collaborated with industry and university partners, who presented the following papers (available at www.sandia.gov/pv):

- *R. Ducey, Richard Chapman, and S. Edwards. The Yuma Proving Ground 900 KVA Photovoltaic Power Station: An Update*
- *J. Moschner, Douglas Ruby, et al. Comparison of Front and Back Surface Passivation Schemes for Silicon Solar Cells*
- *A. Rohatgi, Narasimha, S. and Douglas Ruby. Effective Passivation of the Low Resistivity Silicon Surface by a Rapid Thermal Oxide/PECVD Silicon Nitride Stack and its Application to Passivated Rear and Bifacial Si Solar Cells*
- *B.L. Sopori, James Gee, et al. On the Performance Limiting Behavior of Defect Clusters in Commercial Silicon Solar Cells.*
- *Holly P. Thomas, Ward Bower, Russell Bonn, Thomas D. Hund, et al. Progress in Photovoltaic System and Component Improvements*
- *Y.S. Tsuo, James Gee, et al. Environmentally Benign Silicon Solar Cell Manufacturing*
- *Edwin Witt, Douglas S. Ruby, et al. Manufacturing Improvements in the Photovoltaic Manufacturing Technology (PVMAT) Project*

Sandia creates and distributes a variety of publications on photovoltaic systems and their applications. For a list of these documents, please contact the Photovoltaic Systems Assistance Center:

through e-mail: pvsac@sandia.gov
by phone: 505-844-3698
by FAX: 505-844-6541
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Sandia National Laboratories

Sandia is a partner in the National Center for Photovoltaics and is funded by the U.S. Department of Energy, Office of Photovoltaics and Wind Technology.

Although crystalline-silicon photovoltaic technology is generally considered to be mature at this point, there is still much valuable research to be done in the field. As an example of the kind of research and development work being done at Sandia and at the National Renewable Energy Laboratory, we describe here a new approach that could offer substantial improvements over current processes being used to manufacture photovoltaic modules. In the new concept, all the crystalline-silicon photovoltaic cells are encapsulated and electrically connected in a module in a single step. This reduces the cost to assemble the module by using planar processes that are easy to automate (1) by reducing the number of steps and (2) by eliminating low-throughput (e.g., individual cell tabbing, cell stringing, etc.) steps. We arrived at the concept after evaluating the entire manufacturing process to come up with ideas for reducing steps, which translates into reducing costs. Through research such as this, the crystalline-silicon project at Sandia and the National Renewable Energy Laboratory hopes to assist industry in the rapid development of crystalline-silicon technology.

TOPICS THIS QUARTER

WORLD WIDE WEB
http://www.sandia.gov/pv

Simplified Module Assembly using Back-Contact Crystalline-Silicon Solar Cells

Photovoltaic modules are large-area optoelectronic devices that convert solar radiation directly into electrical energy. They require good electrical and optical performance and, due to the low energy density of solar radiation, exceptionally low manufacturing and material costs to be competitive with other electrical-energy generation technologies.

Most photovoltaic modules now use discrete crystalline-silicon solar cells connected in an electrical circuit and encapsulated with a glass cover and polymer backsheet for environmental protection. Although very successful, the basic design and assembly process of present crystalline-silicon photovoltaic modules are *more than 20 years old.* The module assembly using these cells requires several steps: (1) solder tabs on the front contacts of the cells *individually,* (2) electrically connect the cells by *sequentially* soldering them into a circuit, (3) transfer the fragile electrical circuit to an encapsulation work station, and then (4) encapsulate the cell circuit in the module.

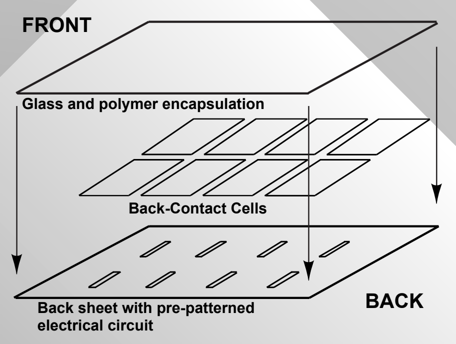

Figure 1. Illustration of monolithic module assembly.

This process typically requires at least three work stations with low throughput and relatively expensive automation. It was adequate when the cost of the silicon substrates completely dominated the cost of the finished module. However, recent advances in growing and wafering crystalline silicon have reduced the cost of the wafer, and now the module assembly and materials are the single largest cost for a crystalline-silicon module for some manufacturers.

It is difficult to automate the assembly of crystalline-silicon modules because of how the contacts to the solar-cell are configured. A back-contact cell, that is, a cell with coplanar contacts on the back surface, avoids the difficult automation and high stress points associated with front-to-back attachment, and allows for planar processes that operate on both contacts in the same step. However, the simpler module assembly using back-contact cells requires increased complexity in manufacturing the cells.

Several methods that may be low-cost for fabricating back-contact cells are being explored by various researchers. For example, researchers at Sandia are working on a concept for a back-contact cell that uses laser-drilled holes in the crystalline-silicon substrate to wrap the emitter from the front surface to the back surface. In addition, back-contact cells are of interest because they may be able to achieve higher performance levels by reducing and/or eliminating optical losses due to grid obscuration.

Back-contact cells allow for radically new module assembly procedures that encapsulate and electrically connect *all* the cells in the module *in a single step.* This new module assembly would use back-contact cells, a module backplane that has the electrical circuit, encapsulant, and backsheet in a single piece ("monolithic backsheet"), and a single-step process to assemble the components into a module (Figure 1). This process reduces costs by reducing the number of steps, eliminating low-throughput (e.g., individual cell tabbing, cell stringing, layout, etc.) steps, and using completely planar processes that are easy to automate. We call this process “monolithic module assembly” because it translates many of the advantages of monolithic module construction of thin-film photovoltaic technology to wafered crystalline-silicon photovoltaic technology.

DESIGN OF THE MODULE

A critical issue lies in selecting a material and process for interconnecting the cells that are compatible with the encapsulation of the back surface. We restricted our development to encapsulation and backsheet materials that have already been used and/or specifically developed for photovoltaic modules, and to vacuum-pressure laminators that are commonly used in fabricating photovoltaic modules. We did this to maximize the project’s success and make the process easier to transfer to production. (Other assembly processes could be considered with new encapsulation materials and processes. In particular, roll-based encapsulation is a continuous process that has potentially very high process throughputs.)

We considered the following interconnect technologies: solder, silver-filled conductive epoxies, and copper foils coated with either pressure-sensitive or thermosetting acrylic-based conductive adhesive. Solder is currently used in photovoltaic module fabrication, and considerable work has been performed to understand the quality and reliability of solder joints. However, we were concerned about obtaining good solder joints during the lamination cycle due to the fluid flow of the surrounding polymer encapsulants and the requirement to completely eliminate fluxes. For this reason, we initially examined conductive acrylic and epoxy adhesives.

Acrylic conductive adhesives are quite attractive; they meet our cost goals, can be precoated on the copper strips, and are believed to be more compatible with the encapsulation materials and processes than the other interconnect options. The reliability of this interconnect is a concern. The conductive epoxies have excellent electrical and mechanical properties, and are believed to be capable of meeting our qualification tests; however, the cost of conductive epoxies is a concern.

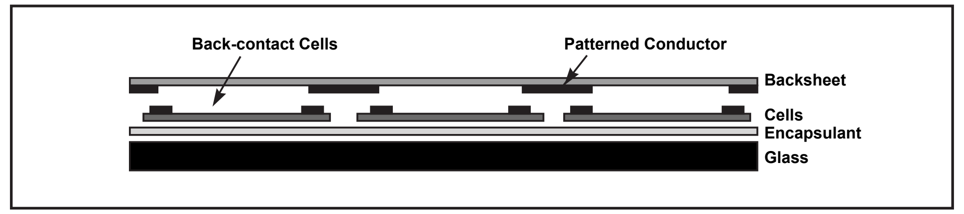

Figure 2. Exploded side view of conductors-on-backsheet monolithic module assembly option.

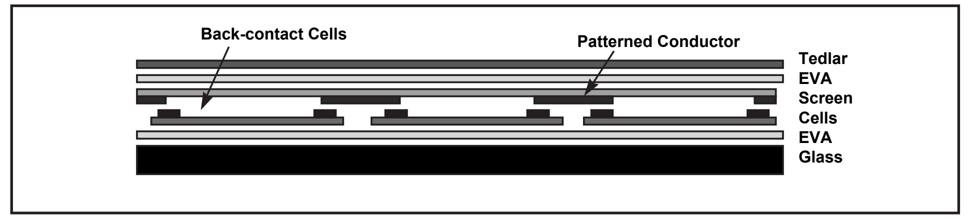

Figure 3. Exploded side view of conductors-on-screen monolithic module assembly option.

We are examining two different assembly processes. The first is very similar to that shown in Figure 1. Copper foil traces are positioned and mounted on the backsheet. The copper foil may be precoated with a conductive adhesive or conductive epoxy. After all the other components (backsheet, cells, front encapsulant, and glass) are positioned, the entire assembly is laminated with a programmed pressure-temperature cycle that initially flows the encapsulation materials and then cures the conductive adhesive and encapsulant. This process uses the same equipment (vacuum laminator) that is used for a conventional photovoltaic module assembly.

We were concerned about the ability of the conductive adhesive to bond to the cell if the surrounding encapsulant melts — which occurs, for example, during a standard lamination cycle using ethylene vinyl acetate (EVA). For this reason, we are using new materials for the backsheet and the front encapsulant with more desirable properties for this application. These materials require a higher lamination temperature than is typically used with EVA and Tedlar™. The higher temperature is also advantageous for reducing the curing time of the conductive adhesive. The resulting structure is shown in Figure 2.

The second assembly process uses a polymer screen to support the electrical circuit (Figure 3). The screen prevents movement of the cell interconnects during lamination, provides positional accuracy of the interconnects, and allows the rear encapsulant to flow through and encapsulate the back surface of the cell. The advantage of this approach is that standard materials (EVA and Tedlar™) can be used. This circuit is also fabricated with the same pre-patterned copper foil used in the first design. After the components are positioned, the entire assembly is laminated using a conventional lamination process.

DEVELOPMENT OF THE MODULE

We tested various aspects of the new module designs in order to demonstrate the concept and determine critical areas for further development.

The interconnects are a significant departure from those used in existing photovoltaic assembly technologies. For this reason, we examined the resistance in these technologies, as seen in Figure 4. (The measured resistance included the bulk resistance of the interconnect material and the interfacial resistances.) All of the materials met our performance goal, although none of the new materials could achieve a resistance as low as Pb:Sn solder. We also performed pull tests on both the acrylic conductive adhesives. The strength of the acrylic-adhesive bonds was about 50% of the strength of our typical die-attach epoxy bonds, which was considered sufficient to further investigate acrylic adhesives.

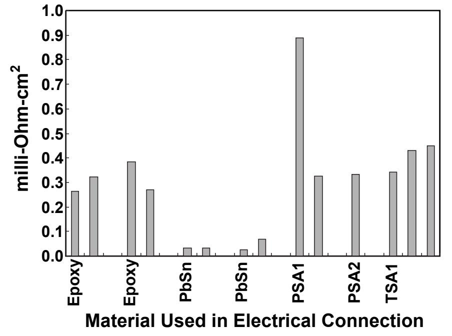

Figure 4. Resistance between copper tabs and a solar-cell silver pad for the following interconnects: silver-loaded epoxy, Pb:Sn solder, two types of pressure-sensitive conductive adhesives (PSA), and thermosetting conductive adhesive (TSA). Several samples of each type were measured. All the interconnects met the target resistance of less than 1 mWcm².

Mechanical prototypes of each design, seen in Figures 2 and 3, were fabricated and thermal cycled (Figure 5). The mechanical prototypes used electrically inactive “cells,” that is, the “cells” were resistance devices with the same grid structure as an actual solar cell. The mechanical prototypes typically had four devices connected in series. The resistance of the mechanical prototypes was

Figure 5. Photograph of the front surface of a monolithic module assembly mechanical prototype. This module used the conductors-on-backsheet design (see Figure 2).

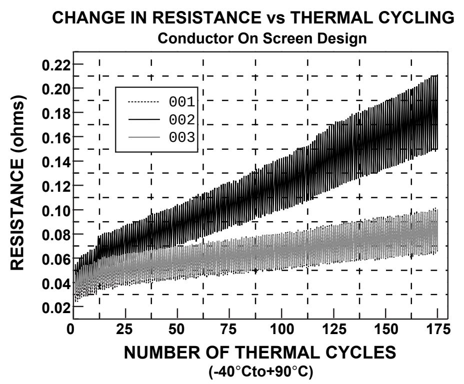

Figure 6. Thermal cycling data for three mechanical modules using conductive epoxy.

monitored to check the assembly process and to monitor changes during thermal cycling. The mechanical prototypes were thermal cycled from -40°C to +90°C, with a dwell time at each temperature of 30 minutes and a total cycle time of 3.5 hours. The mechanical modules were visually examined after 120 cycles.

All the mechanical prototypes had low electrical resistance before thermal cycling, which demonstrated the positional accuracy of the new assembly processes and the good bonds at room temperature. The samples using thermosetting conductive adhesive, however, failed the thermal cycling tests. The resistance of these samples increased dramatically with temperature, and some of these samples would reversibly open circuit. Our particular “thermosetting” adhesive contained, in fact, a significant fraction of pressure-sensitive adhesive (PSA) resins. Samples using 100% thermosetting acrylic adhesive will be tested next, and may perform better than the PSA. It should also be noted that conductive PSAs have been used in applications with similar reliability requirements. We believe that the PSA may require a different application method (e.g., roll lamination) to be successful.

Resistance versus the thermal cycling for three mechanical modules using conductive epoxy is shown in Figure 6. These samples all used the screen-mesh and EVA construction. The epoxy worked better than the conductive adhesive, but there is still a trend toward higher resistance with longer thermal cycling. Conductive epoxies are used in die-attach applications with much more severe thermal cycling requirements. For example, we have used epoxy bonds in applications that required passing thermal cycling tests between -65°C and +175°C. Because we know that the epoxy bond is capable of meeting our technical requirements, we believe that the encapsulation cycle will need to be further tuned to obtain more fully cured bonds. Other issues, such as fatigue, will also need to be investigated. Visual inspection of the modules after 120 cycles showed no delamination of the contacts or encapsulation. More recently, we successfully assembled modules using the monolithic module assembly process, EVA, and low-temperature solders. These mechanical modules have not been thermal cycled yet.

Finally, we fabricated a minimodule using the screen-mesh approach and conductive epoxy (Figure 7). The minimodule had four series-connected back-contact 42-cm² emitter wrap-through (EWT) cells. The average fill factor of the four EWT solar cells was 0.662, while the fill factor of the encapsulated minimodule was 0.663. Hence, the module interconnects in the monolithic module assembly module introduced negligible additional series resistance or shunt conductance. The relatively poor performance of the EWT cells is due to the early development of back-contact cells.

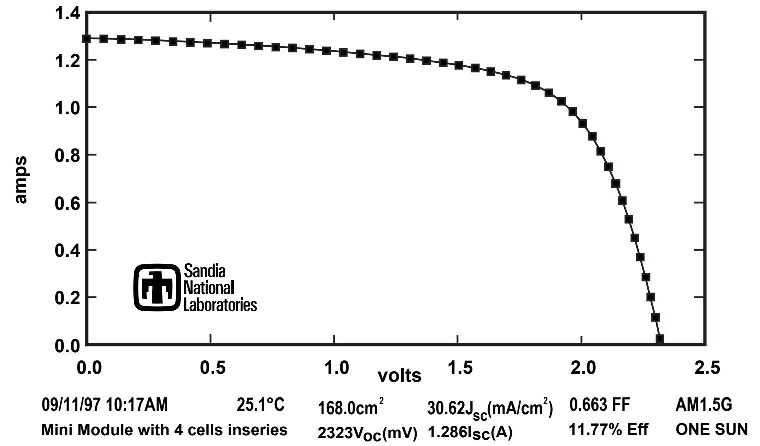

Figure 7. One-sun performance of monolithic module assembly.

COST ANALYSIS

It is difficult to estimate costs for a process that is not fully developed. However, the motivation for work on monolithic module assembly can be demonstrated through some simple cost comparisons.

For the first products that use monolithic module assembly, most of the material costs will be similar to present technology (e.g., glass, encapsulant, and backsheet). Also, we assume that encapsulation equipment and throughputs similar to present industry standards will be used. Hence, the difference in cost is due to the electrical circuit assembly. Our assembly will use pick-and-place equipment to lay the cells out for encapsulation, which will replace the cell tabbing machines, cell stringers, and layout work stations of the present process. We estimate that our concept could achieve a 2X improvement in throughput at half the capital cost of current tab/string machines. We also believe that monolithic module assembly will have improved yield compared to current processes because the processes are more planar. Consequently, a cost reduction of nearly 50% is estimated for labor and capital in the module assembly area of the photovoltaic module manufacturing plant.

The monolithic backsheet with the integrated circuit, encapsulant, and backsheet is manufactured using high-volume roll-to-roll style equipment, which will probably be performed by a vendor. The monolithic backsheet will therefore appear as an increase in material cost to the manufacturer. Assuming a conservative added cost of $15/m² to manufacture the monolithic backsheet (i.e., cost in addition to the material cost of the encapsulant and backsheet), the net savings with monolithic module assembly compared to the current process is estimated to be between 10% and 20% at the module level. Any increased costs for fabrication of the back-contact cell would reduce this potential cost savings. On the other hand, including advanced roll-based encapsulation techniques with monolithic module assembly could achieve even further cost reductions.

For space applications, the photovoltaic community uses back-contact crystalline-silicon solar cells because of their advantages in array assembly. Cost reductions at the array level of 25% have been reported for large photovoltaic arrays that are used in space by using back-contact rather than bifacially contacted solar cells.

This work was originally presented at the 26th IEEE Photovoltaic Specialists conference. We would like to acknowledge the contributions of several industrial colleagues (J. Hanoka and R. Chleboski of Evergreen Solar, and M. Kardauskas of ASE Americas). Specific research for this concept was performed at Sandia.

For more information, please contact James Gee, 505-844-7812, or Ted Ciszek, 303-384-6569. The entire paper is at Sandia's PV website: www.sandia.gov/pv

BRIEFS

New manager for Photovoltaic System Components

James Gee has taken over leadership of Sandia’s Photovoltaic Systems Components Department effective the end of May. The department was formerly led by Marjorie Tatro, who is now manager of the Software Technologies and Development Department, which, like the photovoltaics departments, is in the Energy and Critical Infrastructure Technology Center at Sandia. Tatro’s new assignment focuses on information technologies for a variety of applications, some of them dealing with national security. Her job includes applying these technologies within the energy infrastructure of the United States (oil, gas, and electric power).

Gee has been project leader of the crystalline silicon research and development project at Sandia and is a nationally known expert in that field. Chris Cameron will continue as photovoltaics program manager and manager of the Photovoltaic Systems Applications Department. Gee and Cameron will work closely together to manage overall program activities.

(Contact James Gee, 505-844-7812, jmgee@sandia.gov, or Chris Cameron, 505-844-8161, cpcamer@sandia.gov)

Sandia presents paper on photovoltaics at international workshop

Doug Ruby represented Sandia’s photovoltaic cell development team at a workshop on the “Promotion of Technology Transfer to the Silicon Photovoltaic Industry,” in Frankfurt, Germany, in July. Ruby presented the results of Sandia’s research on plasma processing, “Plasma Etching, Texturing, and Passivation of Silicon Solar Cells.” There was considerable interest in this potentially cost-effective process for significantly increasing the performance of standard production-line, screen-printed cells. Siemens Solar was particularly interested in collaborating on future experi-